EXECUTIVE SUMMARY

I. Study Background

In 2001-2002 the National Academy of Sciences initiated a review of the NASA Solar System Exploration program as part of their Decadal Study. The objective of the Decadal Study is to help NASA prioritize the missions and science objectives for the next ten years. This report is expected to reaffirm the importance that the Solar System Exploration program has in understanding the formation and evolution of the Earth and its inhabitants as well as in the search for life beyond the confines of this planet.

In anticipation of the Decadal Study, Dr. Colleen Hartman, Director of the Solar System Exploration Program, commissioned a working group of NASA's Solar System Exploration Subcommittee (SSES) to examine the technology investment and propose a roadmap to achieve the vision set out by the Decadal Study. Table 1 lists the participants and their affiliations. This report serves as the output of that subgroup.

Name	Affiliation
William Jeffrey, Chairman	Adroit Systems, Inc.
Touraj Assefi	Univ. of Idaho
Bruce Campbell	Smithsonian Institution
Mohamed El-Genk	Univ. of New Mexico
David Hyland	Univ. of Michigan
William Lindsey	Univ. of So. California
Gary Rawitscher, Facilitator	NASA Headquarters

Table 1. List of SSETAG participants with their affiliations.

Prior to this study, NASA Headquarters had developed a taxonomy of research areas. To maintain connection to other NASA efforts, we adopted this taxonomy and have structured this report around it. Table 2 provides the breakout.

1. Information Technology	**5. Avionics for Space Environments**	9. Planetary Protection Technologies
2. Communications	6. Low-Mass Structures	**10. Power Generation, Distribution and Storage**
3. In-Space Propulsion Systems	**7. Guidance, Navigation, and Control**	**11. Science Instruments**
4. Local Mobility and Surface Systems	**8. Entry, Descent and Landing Technologies**	**12. Electronics in Extreme Environments**

Table 2. NASA HQ Technology Taxonomy

The topics in Table 2 highlighted in bold are covered in this report. The topics not covered were due to either being extensive enough to require a dedicated study (Information Technology) or insufficient expertise on the committee to provide technical suggestions (Low-Mass Structures and Planetary Protection).

We further divided the technologies during deliberations into two categories: *Enabling* and *enhancing* technologies. An *enabling* technology is one that allows a mission or science objective to be achieved within a "reasonable" cost constraint.

Without the *enabling* technology, the mission could not be done, or the science objective could not be met. An *enhancing* technology will either improve the science of a mission or reduce its cost. Without the *enhancing* technology, the objective can still be met – but not as "well". This report will provide analysis of, and recommendations for, both *enabling* and *enhancing* technologies for each of the subjects listed in the NASA Taxonomy.

The missions considered by the panel are shown in Figure 3. These missions were the "best guess" as to the direction the decadal study was going to advocate. A workshop was organized by the Jet Propulsion Lab to bring the relevant scientists and technologists together to discuss the science objectives for each of these missions. A summary of the top-level missions is provided in Table 3. These mission objectives were used to identify the resulting *enabling* technologies.

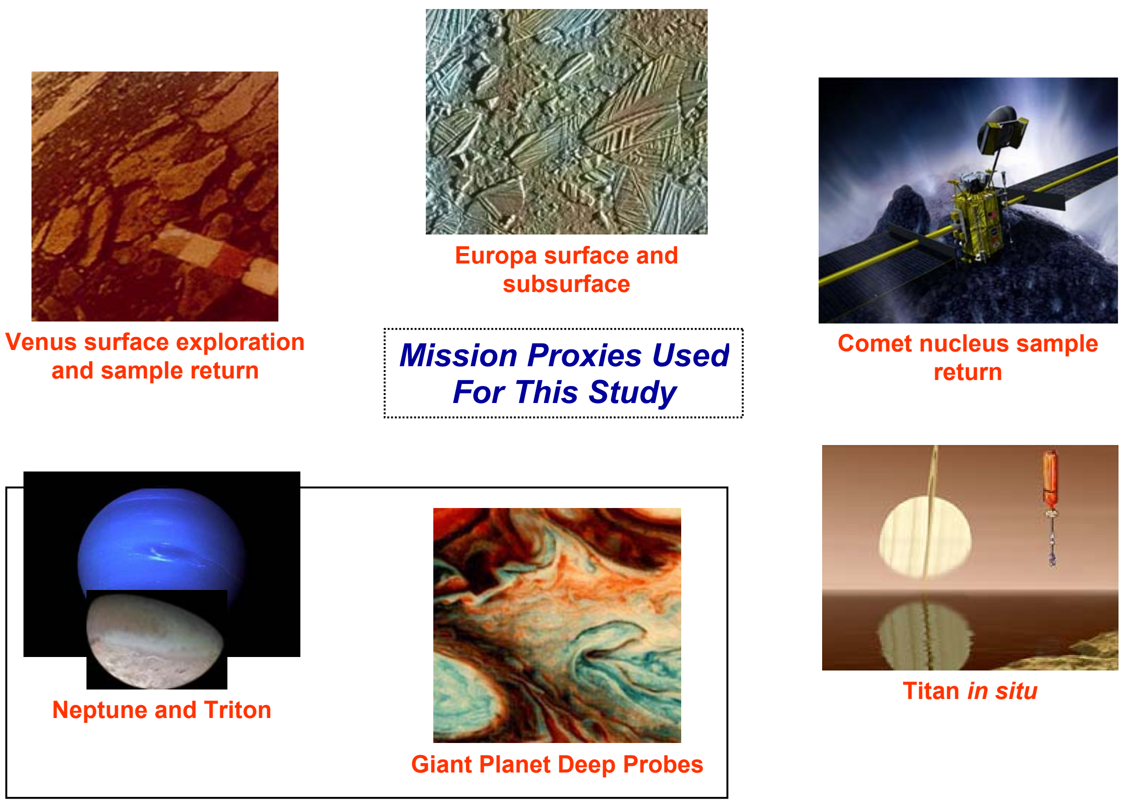

Figure 3: Missions considered for this Report. They were chosen to represent reasonable proxies while awaiting the Decadal Survey Report.

Destination	Objective
Venus	• Sample return • In situ • Long-life mission
Titan	• Aerobot plus orbiter • Aerobot only
Europa	• Orbiter only • Small lander • Large lander
Comets and Asteroids	• "Touch-and-Go" • Deep borer
Gas Giants	• Jupiter deep probe • Neptune / Triton

Table 3. List of specific mission concepts explored.

II. Conclusions and Recommendations

The conclusions and recommendations are the collective judgment of the committee. As such, they represent where we believe additional investment should be made in the technologies to further the scientific goals of the Solar System Exploration Program. The technical rationale (and in some cases the financial benefit anticipated) from a technology investment is provided in the main body of the report.

In attempting this exercise, several observations became apparent that are worth noting – particularly in how they might impact mission specifications:

- Mission scientists implicitly (and somewhat unconsciously now) limit the scientific objectives to what they believe will be either affordable, technically achievable, or within the technical risk acceptable to the mission sponsor. This filtering of ideas often occurs prior to discussions with the engineers. Thus we have in the community an unintentional "damping function" on radical ideas that affects not only that mission – but does not surface the "what ifs…" that could be used to guide future technology investment.

- Technology development often occurs without an explicit quantitative benefit or goal in mind. This creates the illusion of a "sandbox" where the technology is constantly being improved – yet it is not clear how good is "good enough". Without the development tied to specific missions or future concepts, the benefit to further improvement is uncertain. In times of constrained budget, this is an inefficient and undesirable strategy. A noteworthy exception to this approach that we observed was in the communications arena where quantitative benefits and cost trades were conducted. The managers in this area are to be commended for their efforts to incorporate financial analysis tools into their resource allocation plans.

- Assessing cost versus benefit for technology development proved to be extremely difficult in many areas. Several of the technologies investigated have the net effect of reducing component size, weight, and/or power (SWAP) as opposed to enabling a new fundamental capability. As a proxy for the benefit accrued by reducing the SWAP, we investigated the use of utilizing the cost estimating relationship (CER). CERs are typically tied to mass – so a reduction of a certain percentage of the mass can be translated to dollars saved. Reducing power likewise translates to a reduction in the mass of the power system – and hence the CER can be utilized as a proxy.

The following technology categories are presented in the same order as NASA's taxonomy. *Within* each category the recommendations are prioritized. There was no attempt to prioritize *across* categories.

Communications:

1. Proceed with the implementation of Ka-band communications capability as the first step. The initial technology development has largely been done for this frequency band except for some further improvements, primarily on the spacecraft side (e.g., higher-power transmitters or steerable array feeds).

2. Proceed with the development of optical communications technology, including an appropriate set of early flight demonstrations. Detailed assessments of the ground station infrastructure requirements and corresponding technology developments should be pursued.

3. Continue studies and technical assessments of large arrays of smaller antennas to build a solid business case for their use. These studies should include the cost/benefits of implementation alternatives, including placement geometries. Based on these analyses, an appropriate technology validation prototype should be built and tested.

4. Continue to explore high-payoff technologies that have the potential to provide substantially more communication capabilities. These include inflatable antennas, second-generation optical systems, and use of W-band frequencies. Investments should be adequate to perform initial assessments and early technology developments, but significant investments should be deferred pending defendable business case analyses.

5. Support fundamental research that will make possible even more substantial leaps in the future. This includes such things as quantum information-communications and multidimensional data compression theory.

In-Space Propulsion Systems:

1. Aerocapture has the potential to increase the delivered mass while simultaneously decreasing the cost of missions to planetary bodies with atmospheres. The benefit-to-cost of this technology appears significant and we strongly recommend an aggressive program to mature and demonstrate aerocapture for Titan, Mars, and Venus. A New Millennium (or similar demonstration) should be pursued as soon as possible. Given the added complexity and thus risk of employing aerocapture at Neptune, a program to explore the benefits for that planet needs to be considered carefully. Reducing the uncertainty in Neptune's atmospheric composition will decrease the development cost. A quantitative development cost vs. savings needs to be conducted for Neptune.

2. Mini-Magnetospheric Plasma Propulsion (M2P2) (a type of magnetic sail) has tremendous potential but is relatively immature. Given the potential advantages over other proposed propulsion schemes, we recommend an investment to further mature the technology. If the technology continues to look promising, then a flight demonstration will be justified, and will almost certainly be required before the technology is approved for any science mission, given the novelty of the scheme. Preliminary analysis indicates that a variant of M2P2 may be useful for orbital changes of satellites in Earth's orbit (LEO to GEO or changing inclination). Given the tremendous operational benefit to orbital changes with minimal energy penalty -- NASA HQ (with MSFC) should consider approaching DARPA and AFRL to share in the development of this technology.

3. SEP has already demonstrated its potential on the Deep Space 1 mission. Improving its performance is important to enable missions to Europa, Titan, and Neptune. This technology is considered more mature (and hence lower risk) than M2P2. In the near term, it is likely that SEP will provide a tremendous enhancement to outer planetary missions. Longer term, it is possible that this technology will be eclipsed by other propulsion schemes.

4. Solar Sails do not appear to provide a performance advantage over other concepts or even over state-of-the-art chemical systems for the outer planetary missions examined. Solar sails might provide an operational or cost advantage for missions in other NASA science themes or Enterprises, but such missions are not in the purview of this committee. This committee can only state that further investment in solar sail technology for NASA Solar System Exploration is of questionable value.

5. Nuclear propulsion concepts (NEP and/or NTP) also do not offer substantive advantages over other technologies assessed in this report *for the missions considered*. Their strength is in enabling entirely new mission concepts not previously considered possible. We are cautiously optimistic that nuclear propulsion will represent a truly "disruptive" technology for NASA. We fully support NASA's exploration of this technology as it applies to new mission architectures and capabilities.

Local Airborne Mobility:

1. Envelope materials able to tolerate the Venus and Titan environments for the required mission durations are needed. In several cases, because of the dense atmospheres, the areal density requirements for these balloons will not be demanding. The exception is the sample return mission, where the balloon is expected to lift the payload to pressures lower than 100mb in order to maximize the ascent launch vehicle performance.

2. Buoyancy control systems capable of operating at Titan and Venus for months represent a high-leverage technology for achieving vertical and horizontal mobility with minimal energy expenditure. These systems should be validated in both free atmosphere tests and in simulation chambers to build confidence in their performance.

3. Propulsion systems for providing horizontal motion relative to the atmosphere are needed that are compatible with aerial deployment of the blimp. Demonstration that these systems will function over the range of temperatures required for their operation is essential. An end-to-end aerial deployment test of the system with its horizontal mobility system is desirable.

4. Anchoring and sample acquisition systems must be researched to better understand the risk profile of schemes for interacting with the surface of Venus and Titan.

5. Autonomy technology is needed to expand the science return from the Titan Aerobot mission in particular and to provide an autonomous safe-hold capability. Development of a test bed to demonstrate these capabilities is needed. More power-efficient processors will be needed to handle the processing load within the limited power resources available on the aerobot vehicle.

Avionics for Space Environments:

1. *Develop the Next Generation of Avionics*. The X2000 Avionics program, which is developing a new generation of radiation tolerant and radiation hard building block modules for deep space exploration, is a significant contribution and an asset to future NASA missions to deep space. However, it is not clear what plans NASA has for development beyond the current generation of X2000, which is becoming the current state of the art. It is therefore advised that NASA engage in the planning and development of follow-on avionics technologies for space exploration. A partnership with the DOD is advised.

2. *Develop Radiation Tolerant Systems*. The X2000 Avionics, even though driven by the mission to Europa, was originally conceived as a modular, building-block architecture for multiple, deep-space destinations. Substantial shielding has been applied to the avionics, for it to survive in the high-radiation environment of Europa. It is advised that NASA continue to explore a combination of radiation-hard, radiation-tolerant, as

well as COTS technologies where appropriate to find the best balance between cost, risk, and performance for their avionics designs. In particular, NASA is encouraged to continue the path of using commercial foundries to develop radiation-tolerant, but single-event-upset-hard, components, such as the X2000 System Flight Computer (SFC). This trend is also consistent with what the DOD is pursuing. A partnership with the Air Force, which seems to be in place, should continue.

3. *Address the Obsolescence for some Components of X2000*. The most vulnerable components of X2000 from the availability point of view are the COTS components that may not be in production in the future. It is recommended that NASA have a plan to address the issue of obsolescence and availability of COTS components.

4. *Develop Advanced Thermal Control and in situ Electronics for Extreme Environments*. NASA's current avionics development, such as the X2000 Avionics, is designed to operate in a controlled thermal enclosure (-50 C to +70 C). NASA's planned missions to Venus and Titan will take them to extreme temperature environments (Venus +460 C) and Titan (-180 C), in which the avionics cannot operate effectively, or in case of Venus, at all. It is advised that for most solar system exploration missions, X2000 avionics with companion thermal control can be used. However, to achieve the science objectives of some missions, some *in situ* sensors and instruments will have to operate outside the thermal shield. It is thus recommended that NASA should consider working on mission-specific sensor support electronics that can survive in extreme environments. Extensive discussion of operation under extreme environments is presented separately.

5. *Initiate Advanced Avionics Integration for Small Craft*. Most of NASA's current microelectronics and avionics technologies, such as X2000, are applicable to medium- to large-scale spacecraft, orbiters, landers, etc. However, for future 'small' landed missions on Europa (< 30kg), or balloon missions to Titan, or probes to Jupiter, further miniaturization and integration of avionics is mission enabling. In particular, it is recommended that NASA further pursue the development of mixed-signal ASIC technology, which increases the level of microelectronics integration; advanced packaging technologies; and non-conventional 'out-of-the-box' system integration technologies that integrate avionics with the spacecraft structures.

6. *Design Assuming On-Board Autonomy***.** Outer planet exploration missions stress the need for on-board autonomous operations and fault-protection. This in turn stresses the need for on-board advanced computing capabilities and on-board storage capabilities that take NASA beyond the capabilities of the current X2000 avionics. It is therefore advised that NASA consider looking into advances from the COTS, DoD, and other sources that would complement X2000 architecture. For example, there are several technology gaps that are obviously missing in the current X2000 architecture: an L2 cache that will further enhance the performance of the system flight computer; radiation-tolerant, non-volatile memory; etc.

7. *Enhance the X2000 Technology Transfer***.** It is recommended that NASA place more explicit emphasis on Technology Transfer to industry and other institutions interested in avionics technology. Whereas, the X2000 Program has held Industry Briefings and held special sessions at Government Microelectronics and Applications Conferences (GOMAC), NASA would further benefit from a Technology Transfer Plan that is better advertised and understood by the broad industrial base. It should also be noted that a more pro-active conference and journal publication record would have helped get the word out to the industry. It is thus recommended that any new technology initiative in avionics (or other disciplines) place emphasis on Technology Transfer as a top-level objective, with explicit deliverables.

8. *Technology Development Gap: FPGA***.** NASA has traditionally placed resources in the development of radiation tolerant CPUs (Central Processing Units) and ASIC (Application Specific Integrated Circuits) technologies. However, over the past decade, a new form of reconfigurable computing elements has emerged -- Field Programmable Gate Arrays (FPGAs). Whereas, they do not match the performance and radiation tolerance of ASICs, FPGAs can reduce the cost of avionics development. It is thus recommended that NASA take a more pro-active role in investigating the broader use of radiation tolerant FPGAs for both digital and mixed signal technologies. FPGA-based micro-controllers could be used as an effective embedded processing engine for scientific instruments, device drivers, etc.

<u>Guidance, Navigation, and Control:</u>

1. GN&C technologies enable many new functions for large and small bodies. NASA should invest in the following enabling tasks that have not been done before:
   a. Multi-sensor-based autonomous position determination for the reference missions. In the case of the Titan aerial vehicle, it is recommended that the position determination should be with respect to a global system attached to the surface of Titan.
   b. Altitude control at a planet to maintain desired elevation above the surface, and to vary it in a controlled manner to obtain atmospheric measurements. This capability is particularly important for a Titan aerial vehicle.
   c. Lateral and vertical maneuvering of balloons and other aerial vehicles. Attaining this capability is a major challenge that will have to be done by mechanisms that are less predictable than propulsive thrusters or reaction wheels used for traditional spacecraft.
   d. Control descent/ascent for low-gravity body missions that include *in situ* exploration and sample return.

2. Perform research in beacon-less optical communications to obtain precision pointing capability. This would permit accurate pointing to inertially fixed positions with high stability, (e.g., star based references).

Entry, Descent and Landing:

1. Entry technology for missions to Venus and Titan appears to be reasonably in hand. Improvements in TPS technology for outer planet atmospheres can yield substantial gains in mass fraction making it possible to increase the number of probes (extremely important for representative sampling) or enabling any given probe to reach a greater depth. *Hence, the primary focus for future NASA SSE funding of entry technology should be on capabilities for entry into the gas giants and related investments in TPS material development.*

2. The dense atmospheres of both Venus and Titan simplify the design of landing systems. Steerable parachutes, developed in terrestrial applications, would enable precision landing or at least hazard avoidance if that is required. *A research effort focusing on advanced concepts for EDL at Venus and Titan is recommended*.

3. A large lander at Europa needs precision landing, hazard avoidance and robust landing capabilities. Since a Europa mission carries no rover *and* safe target areas are much smaller than a few kilometers because of the abundance of ridges and troughs, precision targeting to 100m-scale accuracy or better is needed. *Accordingly, NASA should invest in the precision technology needed to accomplish this objective*.

4. Development is needed in navigation hardware, such as lidars and radars, in the rapid characterization of the small body environment, in advanced hazard avoidance algorithms, in the capability for hovering, and in the capability for execution of repeated ascents/descents. For the small-body landers it is possible to deploy cooperative retroreflector targets to the surface as MUSES-C proposes to do, to ensure more accurate and reliable ranging. *Building on previous work and coordinating with the needs of a large Europa Lander, NASA should invest in precision landing technology needed for small body sample return*.

5. Anchoring and release technology at both icy and non-icy bodies is needed to enable the acquisition of core samples from comets and asteroids. The uncertainties in surface properties are a major concern that will not be resolved, in all likelihood, before these missions are planned. *Accordingly NASA should invest in approaches to small body anchoring and release that minimize the knowledge that is needed and accommodate the largest range of surface properties.*

Power Generation, Distribution and Storage:

Heat Source Technology Needs:

1. New radioisotope heat sources generating less than one watt and up to 60 watts to serve a variety of potential missions.

2. New radioisotope heat sources to provide the community the option to either release or contain the helium gas without increasing the mass or volume of the power system.
3. New fuel forms, such as the coated particle fuel compact, that offer more flexibility than the clad pellets in the current GHPS and RHUs.
4. New fuel fabrication techniques. NASA should request that DOE consider replacing the granular metallurgy fabrication techniques with Sol-Gel techniques, in which all or most the chemicals used are recycled.

Converter Technology Needs:

1. Funding for Advanced Stirling Engine Converter (ASEC), Alkali Metal Thermal to Electric Converter (AMTEC) and Segmented Thermoelectric (STE) technologies should continue at critical levels to address outstanding technology issue and advance their maturity. Continuation of funding should be based on detailed technical progress reviews at appropriate periods of one to two years.

Space Reactor Power System (SRPS) Technology Needs:

1. Future technology development of SRPS for electric propulsion, whether for ion or hall thrusters, should be carried out with a full understanding and the intention of not only achieving high performance but also, through proper integration with the SRPS, making it possible to develop a low-mass, high-specific-power nuclear electric propulsion system. Spacecraft integration, converter technology and nuclear reactor technology challenges will strongly affect the SRPS mass. All three challenges must be fully investigated prior to any subsystem or component selection for the SRPS.
2. Advanced electric propulsion technology should explore the potential benefits of injecting hot propellant at 800 - 1300 K into the thruster, as this would help develop a low-mass space reactor power system and potentially provide for a low-specific-mass nuclear electric propulsion system.

Energy Storage device Technology:

1. It is recommended that NASA fund Li-Ion liquid organic electrolyte technology and join AFRL in developing this technology for future aerospace missions. The program needs to: (a) improve cycle life and calendar life of lithium ion batteries, (b) develop electrolytes that can enable the operation of these batteries at $\leq$ 215 K, and (c) develop advanced components that can improve the radiation tolerance of batteries.
2. NASA should provide sustained funding to: (a) develop lithium ion conducting polymer electrolytes that are appreciably conductive at and below room temperature, (b) develop composite electrodes that have both ionic and electronic conductivity, and (c) fabricate and test prototype cells with advanced electrolytes and electrode materials.
3. It is recommended that NASA provide funds to improve the rate capability and extend the operating temperature range of lithium solid-state inorganic electrolyte battery technology.

Solar Cell and Array Technology

The following table provides the prioritized needs for NASA in developing advanced solar cell and array technology. The top 5 needs listed are currently being pursued by a variety of Defense and commercial programs. NASA should stay abreast of the development of these technologies. The unique NASA needs that are not being pursued by other groups are in developing low intensity – low temperature (LILT) arrays and radiation resistant arrays. NASA should consider development of these technologies.

Advance Technology	Driving missions	Requirements	State of the art	Needed technology
1) High Power Arrays for SEP	CNSR, outer planets, VSSR, MSR	• >150 W/kg specific power • Operate to 5 AU	• 50-100 W/kg • Unknown LILT effect	• High efficiency cells thin-film cells • High power low -mass
2) Electrostatically Clean Arrays	SEC: MMS, MC GEC, SP, Sentinels	• < 120% of the cost of a conventional array	• ~300% of the cost of a conventional array	• Transparent plastic covers • Glass covers for multiple cells
3) Mars Arrays for dust environment	MSL, MSR, Scouts	• 26% efficiency • >180 sols @ 90% of full power	• 24% efficiency • 90 sols @ 80% of full power	• Optimized cells for Mars • Dust mitigation
4) High Temperature Solar Arrays	Solar Probe, Sentinels, PASO	• ≥350°C operation (higher temperatures reduce risk)	• 130°C steady state; 260°C for short periods	• Adapt cells and arrays to high temperatures based on AFRL tech
5) High Efficiency Cells	All missions	• > 30+ %	• 27%	• Adapt AFRL and commercial progress to NASA needs
6) LILT Resistant Arrays	Outer planet missions, SEP missions	• No insidious reduction of power under LILT conditions	• Uncertain behavior of MJ cells under LILT conditions	•Adapt cells/arrays to avoid LILT problems • Test cells at LILT conditions
7) Radiation Resistant Arrays	Europa and Jupiter missions	Radiation resistance with minimal weight and risk penalty	• Thick cover glass	• Radiation resistance thin film and concentrator arrays • Adapt commercial and military cells to meet radiation requirements

<u>Science Instruments:</u>

The following table presents a prioritized summary of <u>instrument</u> development. In addition, there is need to support development efforts on enabling <u>subcomponents</u>.

On a programmatic level:

(1) Begin the science definition process for these missions much earlier (3-4 years prior to the Announcement of Opportunity) than is typical. Define specific measurement requirements relevant to the science goals.

(2) Fund short, specific studies to assess which instrument designs can be miniaturized while providing the needed sensitivity. For example,
   i. Wet chemistry labs and miniature organics detectors – can these satisfy the science questions within volume/mass/power constraints?

ii. Gas Chromatograph / Mass Spectrometer (GC/MS) systems for planetary atmospheres – are there technical limits to the sensitivity as a function of instrument mass?
iii. Requirements for sample delivery and preparation – can reasonable spacecraft drills, corers, or sampling arms be implemented?

(3) Based on the results of the above studies, fund rapid development of brass-board demonstration units.
(4) Improve facilities for instrument testing under realistic conditions.

Priority	Technology	Rationale for Priority	Current Gaps
1	Mini-GC/MS	Venus deep atmosphere probes Age dating systems Outer planet atmosphere/surface Comet surface and dust	Several instruments previously funded by PIDDP. Need firm performance targets for particular missions. Trades of precision/integration time vs. mass, power, volume. Sample delivery and concentration (e.g., laser ablation)
2	Biotic/prebiotic detection and analysis	Mars, Europa surface and subsurface Titan, comets	Performance targets: detection vs. characterization. Comparison of viable instrument techniques: capillary electrophoresis, wet chemistry, GC, Raman. Sample delivery and concentration (e.g., valves).
3	Sample collection and delivery mechanisms	Delivery of samples to GCMS, wet chemistry labs, microscopes, etc.	Each sampling system is tailored and expensive. Lots of good ideas, but few beyond breadboard stage. Laser ablation, drills, diggers, scrapers, etc.
4	Geophysical systems	Subsurface probing by radar, seismic methods. New technologies for nuclear magnetic resonance, deep EM sounding.	Miniaturization of radar systems and seismic sensors underway. Limited challenges to achieve target goals. Uncertain need for NMR and other new technologies.
5	Mineralogic characterization	Raman, Mossbauer, X-ray diffraction/fluorescence	Numerous PIDDP-level efforts. Varying challenges with sample orientation and preparation.
6	Imaging systems	Required by most planetary missions	Few – APS, CCD, and TIR detectors flight-ready. Microscopes demonstrated for MER mission.
	Environmental test capability	High and low temperature and pressure environments (Venus, Europa).	Not ranked, but basic test facilities considered essential. Extensive development of simulated terrains or materials less crucial.

<u>Electronics in Extreme Environments:</u>

1. Develop high-temperature and high-pressure passive thermal control technologies such as thermal insulation, thermal storage, thermal switches, and insulated pressure vessels. Similarly, in the thermal control technologies for low- temperature environments, lightweight thermal insulation and thermal energy management systems need to be developed.

2. Develop high-temperature sample acquisition systems as well as high-temperature sensors and actuators. Sensor and actuator electronic interfaces should be based on SiC and use high-temperature ceramic packaging. High-temperature mechanisms for sample acquisition as well as high-temperature power storage should be also developed to provide power to components operating outside thermal control enclosure.

3. Develop low-temperature (-180 C) capabilities in the area of electronics, sensors, and actuators that are enabling for Titan and CNSR class missions. .

4. In light of the new NASA nuclear power initiative, investigate new mission scenarios for Venus exploration including long-duration missions enabled by active refrigeration.